

(NASA-CR-174766-Vol-1) ENERGY EFFICIENT
ENGINE PROGRAM TECHNOLOGY BENEFIT/COST
STUDY. VOLUME 1: EXECUTIVE SUMMARY (PMA)
CSCL 21E
19 D

G3/07

Unclass
0304590

N90-29564

FEED

NASA

ENERGY EFFICIENT ENGINE PROGRAM
TECHNOLOGY BENEFIT/COST STUDY
VOLUME I

EXECUTIVE SUMMARY

by

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UNITED TECHNOLOGIES CORPORATION
Pratt & Whitney
Engineering Division

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Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Lewis Research Center
Cleveland, Ohio 44135

Contract NAS3-20646

NASA CR-174766
PMA-5594-258

19p.

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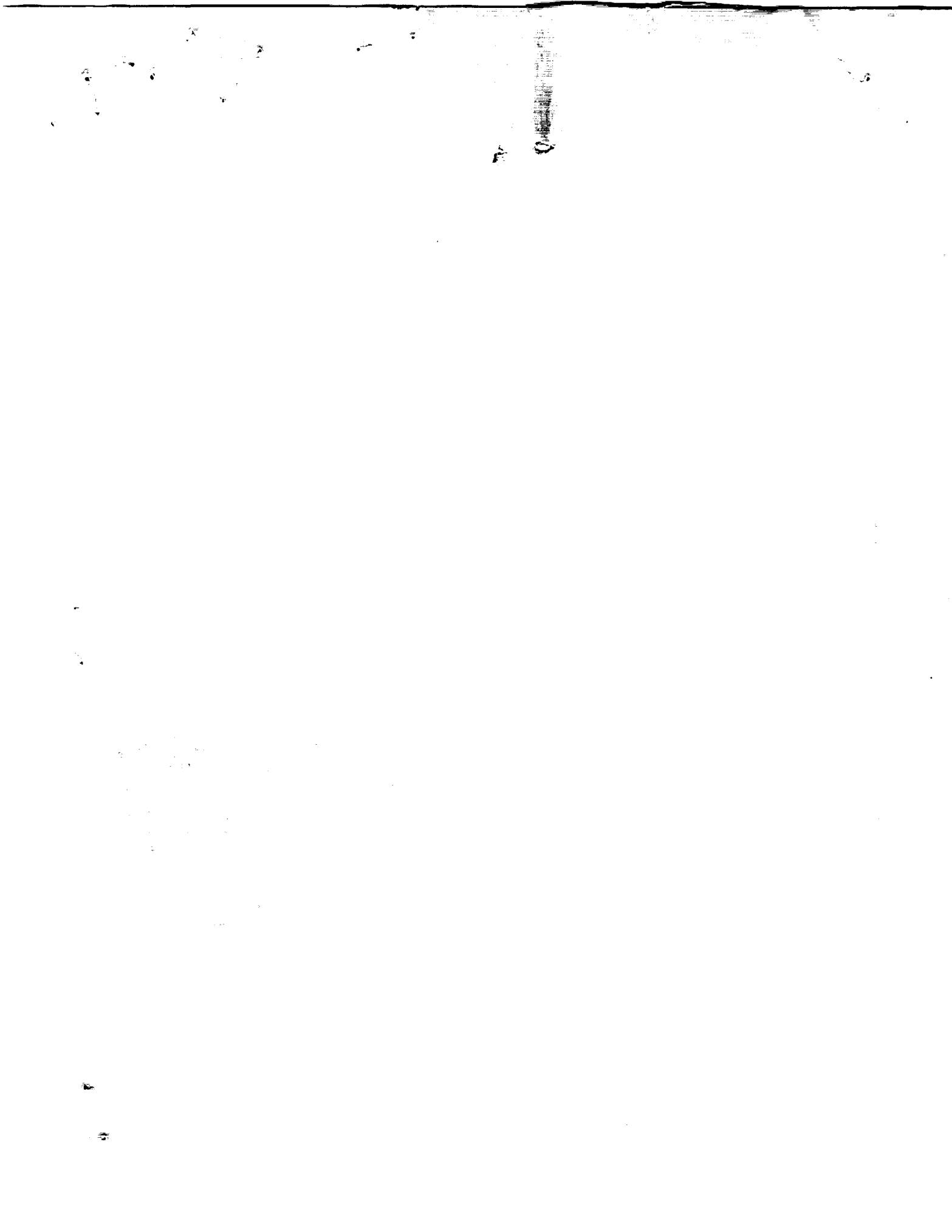


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SECTION 1 -- SUMMARY

Pratt & Whitney completed a comprehensive study of far-term technology requirements and their benefits for commercial aircraft engines beyond the year 2000. This effort -- the Benefit/Cost Study -- was conducted under the NASA-sponsored Energy Efficient Engine program. It showed that the benefits derived from high technology advancements are far from exhausted, and there is a potential for significant savings in both fuel consumption and operating costs.

In examining the merits of technology advances, a series of cycle, mechanical and economic analyses was conducted to identify promising advanced engine concepts. Analyses identified a geared-fan, separate exhaust configuration with a bypass ratio between 9 to 12:1 and overall pressure ratio between 55 to 65:1 as providing large savings. Compared to a refined version of the Energy Efficient Engine, the advanced engine concept lowered fuel burned by up to 24 percent and operating costs by up to 14 percent. These savings are attributed to the following nine advanced concepts, and as part of the Benefit/Cost Study, programs have been defined to bring each technology to a state of readiness.

- Short, slim nacelles
- Swept fan blades
- High speed turbines with improved materials
- Low Loss diffuser/combustor with improved materials
- Reduction gearing with improved materials and cooling
- Highly-loaded compressors
- Closed-loop active clearance control
- Fully-damped high speed rotors
- Structural composites

The results of this study have pointed to the direction for future research. To obtain the large potential savings offered by technology advancements, it is imperative to develop a technology base that permits engines to operate at significantly higher overall pressure ratios and bypass ratios.

SECTION 2 -- INTRODUCTION

The Energy Efficient Engine Component Development and Integration program is an effort sponsored by the National Aeronautics and Space Administration. It is directed toward identifying and verifying technology advances that can substantially lower both the fuel usage and the operating costs of future commercial aircraft engines. As part of the Energy Efficient Engine program, Pratt & Whitney completed a Benefit/Cost study of commercial aircraft engines beyond the year 2000. This study focused on identifying far-term technology requirements, assessing their benefits and formulating programs to bring the technologies to a state of readiness.

The Benefit/Cost study was conducted in a series of steps. First, performance trends were projected for the study time period. Cycle studies were then conducted and flowpaths were defined for eight advanced cycles. After selecting the three most attractive concepts, mechanical configurations of the candidate engines were defined to identify unique technology requirements. Next, performance and economic analyses were conducted to quantify the benefits of the far-term technologies. Finally, an individual technology readiness program was formulated for each concept.

Fuel burned and direct operating cost plus interest were the main evaluation parameters used in this study. In assessing the benefits of a concept, the change in these parameters was determined relative to a refined version of the Energy Efficient Engine's flight propulsion system. This refined engine, which is based on a 1988 level of technology, offers savings of over 20 percent in fuel usage and over 10 percent in operating cost compared to the Pratt & Whitney JT9D-7A reference engine.

This report summarizes the salient results from this study. Details of the various analyses are contained in Volume II.

SECTION 3 -- ENGINE DEFINITION

TECHNOLOGY TRENDS

In establishing a base for engine and cycle definitions, technology trends were projected to ascertain the expected level of component performance in the 2000 to 2010 time frame. Overall engine efficiency, which is proportional to the inverse of thrust specific fuel consumption, has increased steadily over the past 30 years. This upward trend, as shown in Figure 1, is projected to continue.

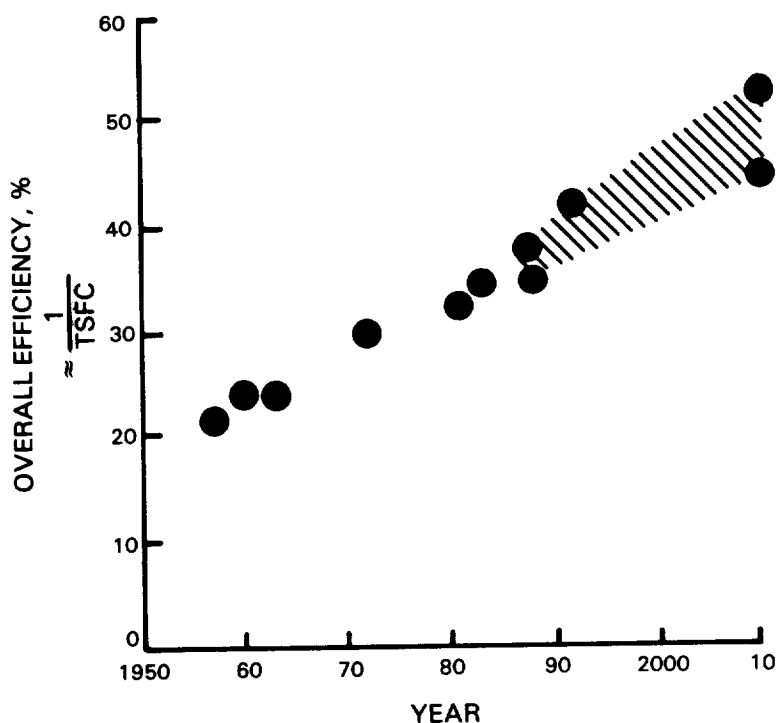


Figure 1 Overall Efficiency Trends -- The trend for higher system efficiency is expected to continue upward on the basis of increases in component efficiency, overall pressure ratio and bypass ratio.

Higher levels of overall efficiency are the result of projected increases in engine pressure ratio, component efficiency and bypass ratio. The operating levels of engine pressure ratio and bypass ratio are expected to nearly double over the next 25 years. However, only moderate increases in component efficiency and combustor exit temperature are anticipated for commercial aircraft engines.

CYCLE ANALYSES

Key cycle parameters were studied parametrically to define candidate cycles for an advanced propulsion system. First, a range of overall engine pressure ratios and combustor exit temperatures was evaluated, using projected component efficiencies and maintaining a constant fan pressure ratio. The results in Figure 2 indicate that cycle trends favor increasing overall pressure ratio. For a large, 266,892 N (60,000 lb) thrust engine, the lowest fuel usage was at pressure ratios between 60 and 65:1. No appreciable overall efficiency benefit was shown for increasing the cruise combustor exit temperature beyond 1315°C (2400°F).

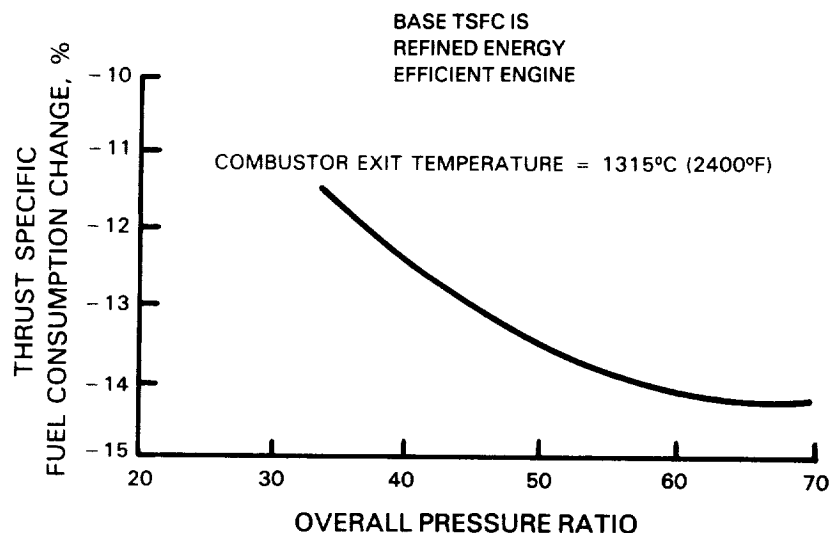


Figure 2 Cycle Trends -- Trends favor increasing overall pressure ratio to levels between 60 and 65:1 for large gains in fuel efficiency.

In other analyses, the affects of varying fan pressure ratio and bypass ratio while maintaining a constant engine pressure ratio and combustor exit temperature were examined. For a given level of component technology, a unique relationship exists between fan pressure ratio and bypass ratio for optimum propulsion system operation. Figure 3 shows that fuel usage decreases with increasing the bypass ratio, thereby decreasing fan pressure ratio. However, the technical challenge is keeping the engine diameter to dimensions that are compatible with airplane integration. Even with advances in nacelle technology, bypass ratios higher than 13:1 may be limited by acceptable engine diameter.

Candidate Cycles

On the basis of these results, eight cycles were selected for flowpath definition and further analysis. These cycles ranged in bypass ratios from 9 to 21 and overall pressure ratios from 46 to 64. Two cycles were defined for a 111,200 N (25,000 lb) thrust size, while the remainder were defined for a 266,880 N (60,000 lb) thrust size. In addition, the spool configurations consisted of a mixture of both direct drive and geared systems with either two or three spools.

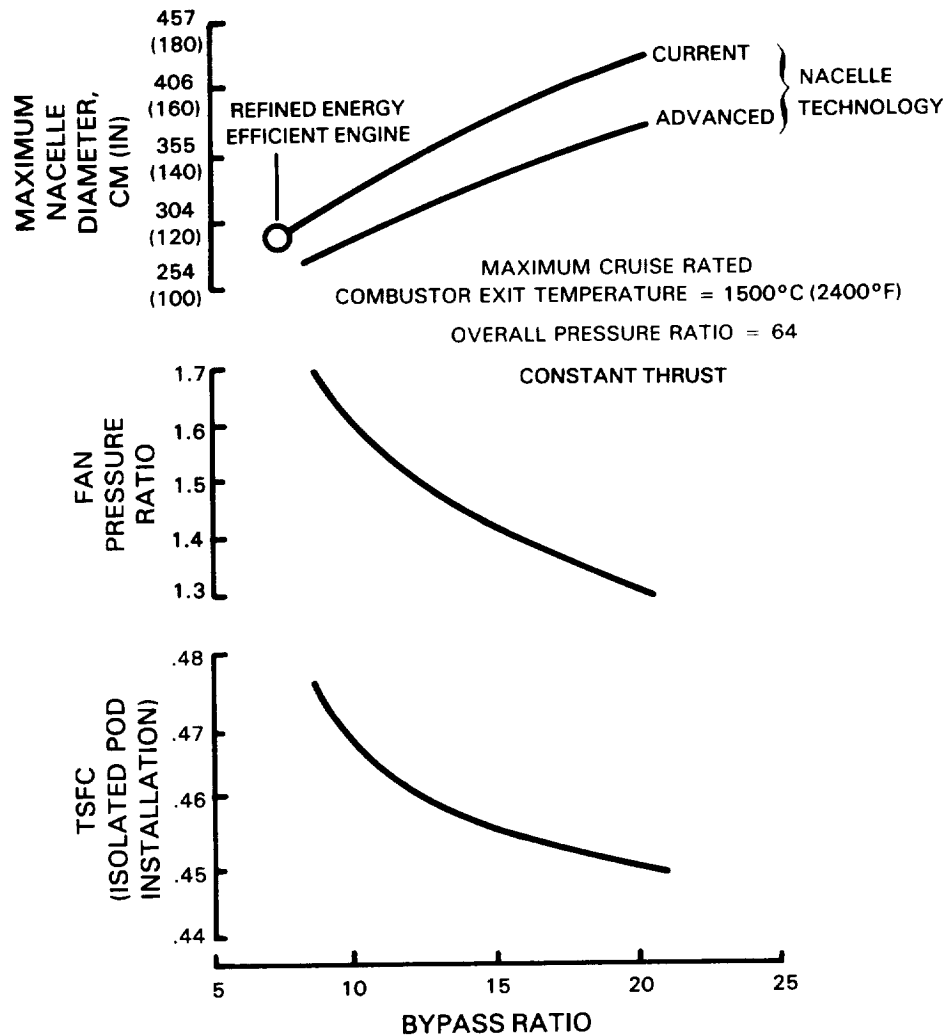


Figure 3 Bypass Ratio Trends -- Increasing the bypass ratio reduces fuel consumption.

In selecting three candidate engines, installed fuel consumption trends were evaluated for the configurations that evolved from the flowpath analyses. These results are presented in Figure 4 and show the advantage of a high bypass ratio, geared system with separate exhaust flow. Based on these considerations, the candidate geared, separate exhaust flowpaths summarized in Table I were selected for the mechanical design studies. These include both a two and a three spool configuration in the 266,880 N (60,000 lb) thrust size, and a two-spool configuration in the 111,200 N (25,000 lb) thrust size.

TABLE I
SUMMARY OF FINAL THREE FLOWPATH CANDIDATES

	Reference Engine	266,800 N (60,000 lb) Thrust Size		11,200 N (25,000 lb) Thrust Size
		Two Spool	Three Spool	Two Spool
<u>CYCLE</u>				
Inlet Flow, kg/sec (lb/sec)	679 (1498)	1184 (2612)	1184 (2612)	504 (1112)
Fan Pressure Ratio	1.65	1.53	1.53	1.53
Bypass Ratio	7.2	12.8	12.8	12.5
Overall Pressure Ratio	38.6	64.0	64.0	55.0
Combustor Exit Temp., °C (°F)	1268 (2315)	1329 (2425)	1329 (2425)	1329 (2425)
<u>FAN</u>				
OD Fan Pressure Ratio	1.65	1.50	1.50	1.50
Tip Diameter, cm (in)	215.9 (85.0)	271.2 (106.8)	274.0 (107.9)	172.2 (67.8)
Inlet Hub/Tip Ratio	0.340	0.260	0.260	0.260
Corrected Tip Speed, m/sec (ft/sec)	441 (1450)	356 (1170)	356 (1170)	356 (1170)
Number of Airfoils	36	24	24	24
<u>LOW-PRESSURE COMPRESSOR</u>				
Pressure Ratio	1.84	2.52	2.05	2.15
Number of Stages	4	3	3	3
Average Aspect Ratio	2.30	1.90	1.90	1.91
Rotor Speed, rpm	3620	7245	7377	11,183
Number of Airfoils	764	253	186	224
<u>INTERMEDIATE PRESSURE COMPRESSOR</u>				
Pressure Ratio	N/A	N/A	4.92	N/A
Number of Stages	N/A	N/A	5	
Average Aspect Ratio	N/A	N/A	1.50	
Rotor Speed, rpm	N/A	N/A	10,856	
Number of Airfoils	N/A	N/A	346	
<u>INTERMEDIATE CASE</u>				
Length, cm (in)	39.6 (15.6)	37.5 (14.8)	23.62 (9.30) (IPC-HPC)	18.54 (7.30)
Inner Radius, cm (in)	24.89 (9.80)	21.08 (8.30)	8.20 (3.23)	7.62 (3.00)
<u>HIGH-PRESSURE COMPRESSOR (Axial Only)</u>				
Pressure Ratio	14.0	20.0	5.00	6.00
Number of Stages	10	11	7	6
Rotor Speed, rpm	13,176	17,640	20,710	22,182
Number of Airfoils	1265	1014	837	537

TABLE I (continued)

	Reference Engine	266,800 N (60,000 lb) Thrust Size		11,200 N (25,000 lb) Thrust Size
		Two Spool	Three Spool	Two Spool
<u>HIGH-PRESSURE COMPRESSOR (Centrifugal)</u>				
Pressure Ratio	N/A	N/A	N/A	3.35
Specific Speed	N/A	N/A	N/A	72.5
Maximum Tip Speed, m/sec (ft/sec)	N/A	N/A	N/A	651 (2139)
<u>COMBUSTOR</u>				
Configuration	Axial	Axial	Axial	Radial Inflow
Length, cm (in)	38.1 (15.0)	35.0 (13.8)	35.0 (13.8)	27.4 (10.8)
Space Heating Rate, M Btu/hr (ft ³) (atmos)	5.1	7.0	7.0	3.0
Combustion Length, cm (in)	20.5 (8.1)	17.7 (7.0)	17.7 (7.0)	17.7 (7.0)
<u>HIGH-PRESSURE TURBINE</u>				
Expansion Ratio	4.00	4.60	2.50	4.78
Velocity Ratio	0.64	0.65	0.63	0.650
Number of Stages	2	2	1	2
Number of Airfoils	149	130	49	104
AN ² (x10 ¹⁰), (in ²)(rpm ²)	5.0	6.0	6.2	6.0
<u>INTERMEDIATE PRESSURE TURBINE</u>				
Expansion Ratio	N/A	N/A	1.94	N/A
Velocity Ratio	N/A	N/A	0.630	N/A
Number of Stages	N/A	N/A	1	N/A
Number of Airfoils	N/A	N/A	65	N/A
AN ² (x10 ¹⁰), (in ²)(rpm ²)	N/A	N/A	5.0	N/A
<u>TRANSITION DUCT</u>				
Length, cm (in)	23.36 (9.20)	9.95 (3.92)	Close- Coupled	3.04 (1.20)
Area Ratio	1.22	1.10		
<u>LOW-PRESSURE TURBINE</u>				
Expansion Ratio	6.10	10.8	9.705	8.33
Velocity Ratio	0.49	0.60	0.564	0.580
Number of Stages	5	5	5	4
Number of Airfoils	1119	812	752	617
AN ² (x10 ¹⁰), (in ²)(rpm ²)	1.68	6.60	6.85	6.62

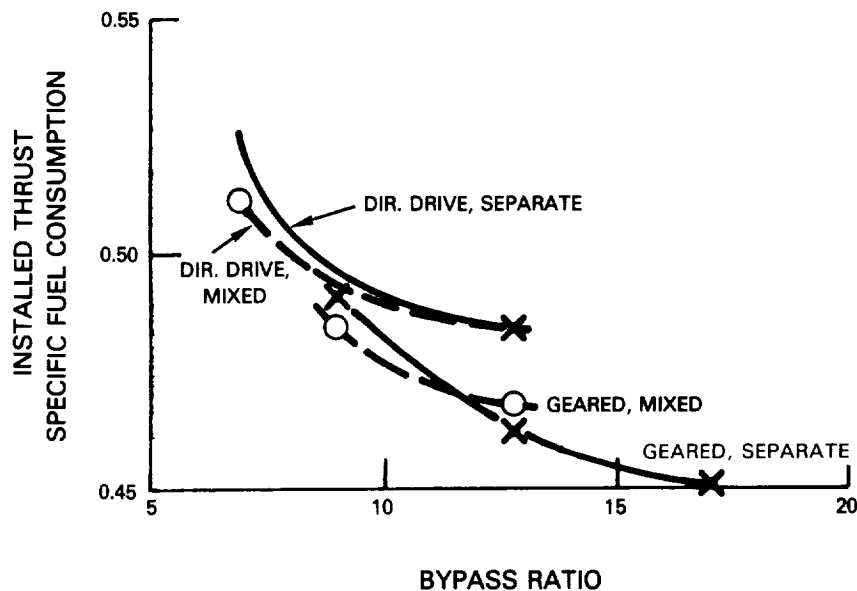


Figure 4 Fuel Consumption Results -- Geared-fan configurations are superior in lowering fuel usage compared to direct drive systems.

MECHANICAL DEFINITION

Figure 5 shows the conceptual mechanical design of an advanced turbofan engine. Although the engine in this figure is a two-spool system in the 266,880 N (60,000 lb) thrust size, the configuration and applied technologies are representative of the other two engine concepts.

The engine is characterized by very high speed, small diameter compressors and turbines and a relatively slow speed, large diameter fan driven through gears by the high speed low-pressure turbine. Nine major technology advances are necessary to achieve the projected overall efficiency increase.

Swept Fan Blades -- This concept offers significant performance gains by reducing shock losses, eliminating the part-span shroud and using a three-dimensional design process. Other features include lower component weight from the hollow titanium blades and a disk made of a composite-reinforced alloy. The potential efficiency improvement of a swept blade, relative to the shrouded design in the reference engine, could be as high as 4 percent.

Reduction Gearing with Improved Materials and Cooling -- Efficiency improvements in the high speed low-pressure turbine and the relatively slow speed fan are very dependent on a highly efficient gearing system. The design is based on stiff shafting and casing to minimize deflections and deformations. The type of gearing arrangement envisioned uses gears and bearings fabricated from advanced materials and lubricants with greater load carrying capability. High strength gear materials offer up to a 45 percent improvement in strength, thereby allowing smaller gears than in service today. These advances could provide a gear system efficiency greater than 99 percent.

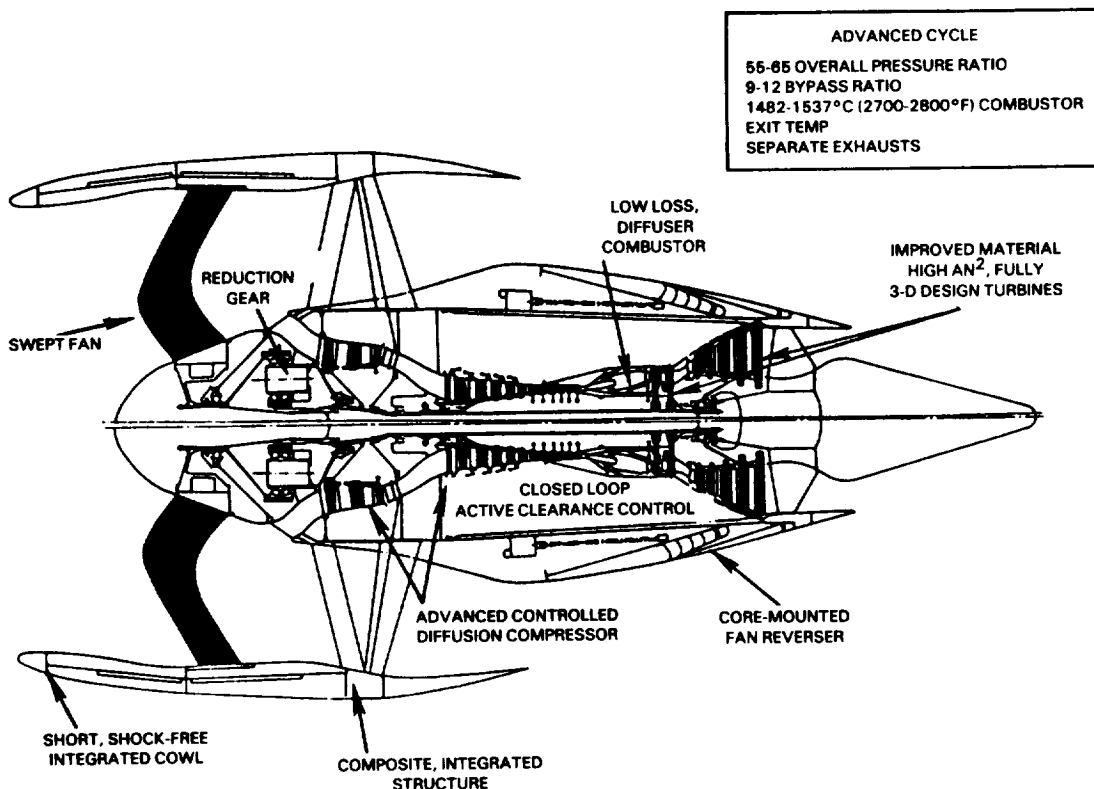


Figure 5 Conceptual Engine Definition -- The prominent mechanical design features are a geared low-pressure spool, swept fan blade and slim line nacelle.

Highly-Loaded Compressors -- Advances in both compressor aerodynamics and materials are required for the highly-loaded compressor in a future engine. In addition, with the small size of the 111,200 N (25,000 lb) thrust size engine, the high pressure ratio cycle could lead to requirement for centrifugal staging in the rear compressor stages. In terms of aerodynamics, the compressor concept is based on advanced controlled diffusion airfoils with three-dimensionally designed endwalls and tighter operating clearances from an improved active clearance control system. Also, operating at the high aerodynamic loading reduces the number of airfoils by over 20 percent, which contributes to a substantial savings in weight and maintenance cost.

The blades in the low-pressure compressor are fabricated from advanced aluminum alloys. In the front stages of the high-pressure compressor, the blades are fabricated from titanium alloys and bonded to a titanium drum rotor. In the rear stages, advanced nickel alloy blades are bonded to a nickel alloy rotor. With all of these technology features, the projected polytropic efficiency is over 93 percent.

Low Loss Diffuser/Combustor with Improved Materials -- The combustor is a compact, single-stage design with a low pressure loss and low pattern factor. The diffuser is a high performance channel design that supplies combustion and turbine cooling air at a low pressure loss. Advanced materials are fundamental to the design of both the diffuser and the combustor liner to permit operation at the higher temperatures associated with the higher overall pressure ratio. The segmented liners are fabricated from a nonmetallic material, such as a ceramic composite, for a temperature capability of 1205°C (2200°F). A non-metallic is also used for the diffuser, while the diffuser case is made from a high temperature alloy with good castability and weldability properties.

High Speed Turbine with Improved Materials -- Both the high and low-pressure turbines operate at high speed. In comparison to the reference engine, the high-pressure turbine operates at a 25 percent higher AN² level (annulus area times speed squared -- a parameter that relates both performance and blade stress parameters) and the low-pressure turbine at approximately 300 percent higher. Airfoils are a three-dimensional design, and leakage losses are controlled by advanced sealing techniques.

The technology in the two-stage high-pressure turbine enables up to 10 percent less cooling air. Advanced disk materials provide a 25 percent improvement in strength, and a single crystal superalloy, in combination with an advanced thermal barrier coating, allows the blades and vanes to operate at up to 222 °C (400°F) higher temperature. A ceramic material is a possibility for the vanes.

Closed-Loop Active Clearance Control -- Clearances as tight as 0.025 cm (0.010 in) are maintained in both the compressor and turbines by a dual active clearance control system. With this concept, a primary system uses a sensing device to provide continual feedback to the engine control so minimum clearances are maintained during steady state operation. This sensor could utilize advanced laser optics or microwave beam technology. The secondary system features a seal translation device for responsive actuation during transient as well as less rapid speed variations.

Fully Damped, High Speed Rotors -- The engine is designed for significantly higher rim speeds and lower hub-to-tip ratios. Meeting the challenges of high speed operation is largely dependent on the anticipated advances in the strength and temperature capability of rotor materials, and the application of high energy absorption dampers. Main shaft bearings are designed to withstand higher centrifugal loading and achieve a life factor 40 percent higher than current bearings.

Structural Composites -- Advanced composites and composite-reinforced alloys are used extensively because of their low weight and high strength properties. In the nacelle, composites are used for the inlet, fan cowl, fan nozzle, fan discharge, and fan reverser. Composite-reinforced alloys are also used for the fan disk and the reduction gear housing. In the high-pressure rotor, local reinforcement with polymeric composites provides a 35 percent weight savings.

Short, Slim Nacelle -- The nacelle has several prominent features to enhance both aerodynamic performance and structural rigidity. A slim line design is critical for integrating higher bypass ratio engines in the airplane as well as reducing the potential high drag and weight penalties inherent in a large structure. The outer fan cowl is a short, thin, shock-free structure, and it is an integral part of the engine structure to reduce deflections and weight. The inner cowl provides structural support as well as stiffness for the gas generator core. Added stiffness is especially important to maintain tight operating clearances with the more flexible smaller diameter core. To reduce the thickness of the outer cowl, the entire reverser mechanism is contained within the inner cowl. The design also includes advances in sound reduction techniques. As mentioned earlier, the use of composites has a large part in reducing component weight.

SECTION 4 -- PERFORMANCE AND ECONOMIC ASSESSMENT

In examining the benefits of far-term technologies, the figures of merit were the change in fuel burned and direct operating cost plus interest relative to the reference engine. Fuel burned is the total fuel used throughout the flight cycle. Direct operating cost plus interest includes costs directly affected by the engine, and for a more accurate representation of the overall economic picture, it accounts for the cost of money.

Four engine concepts, covering mixed and separate flows as well as direct and geared fan, were evaluated parametrically in three advanced airplanes. Also, three levels of fuel prices \$0.26, \$0.40 and \$0.66 per liter, (\$1.00, \$1.50 and \$2.50 per gallon) were used in the analysis. As shown in Figure 6, the nonmixed, geared-turbofan offers superior savings in both fuel consumption and operating economics in comparison to the other concepts. Fuel savings of up to 24 percent and reductions in direct operating cost plus interest of up to 14 percent are possible.

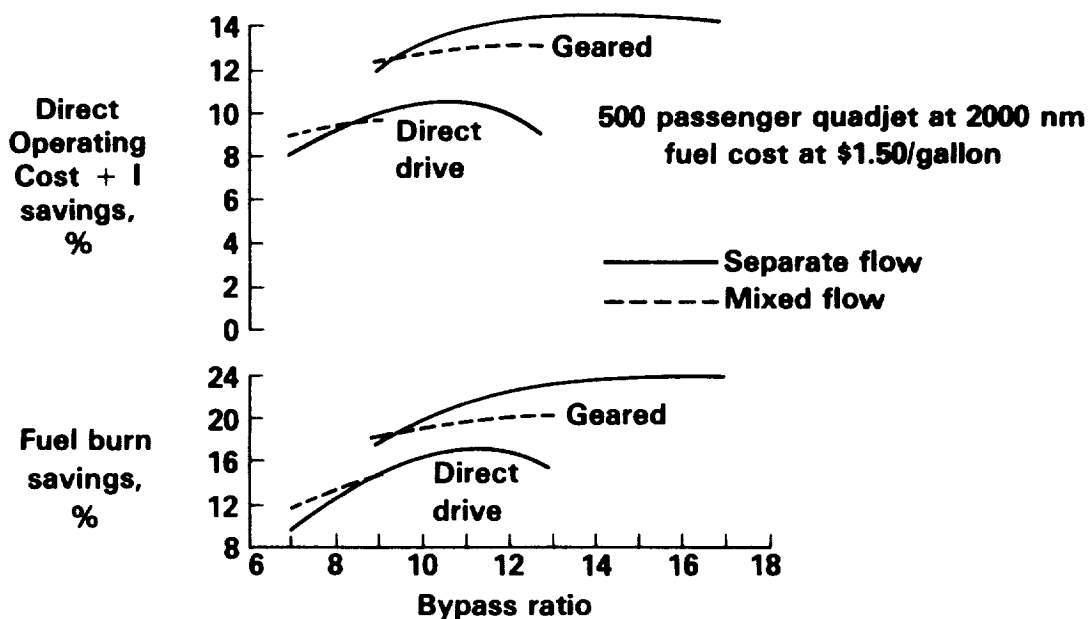


Figure 6 Technology Benefit Summary -- A geared-fan configuration with a separate exhaust offers the highest savings in fuel and operating costs.

SECTION 5 -- TECHNOLOGY PROGRAMS

A technology plan has been formulated to bring these nine key technologies to a state of readiness. The plan identifies the different areas of each technology requiring research and development programs. Each program has been defined in terms of the program objective, scope of work, cost, and scheduling. Figure 7 shows the comprehensive technology plan for achieving technology readiness.

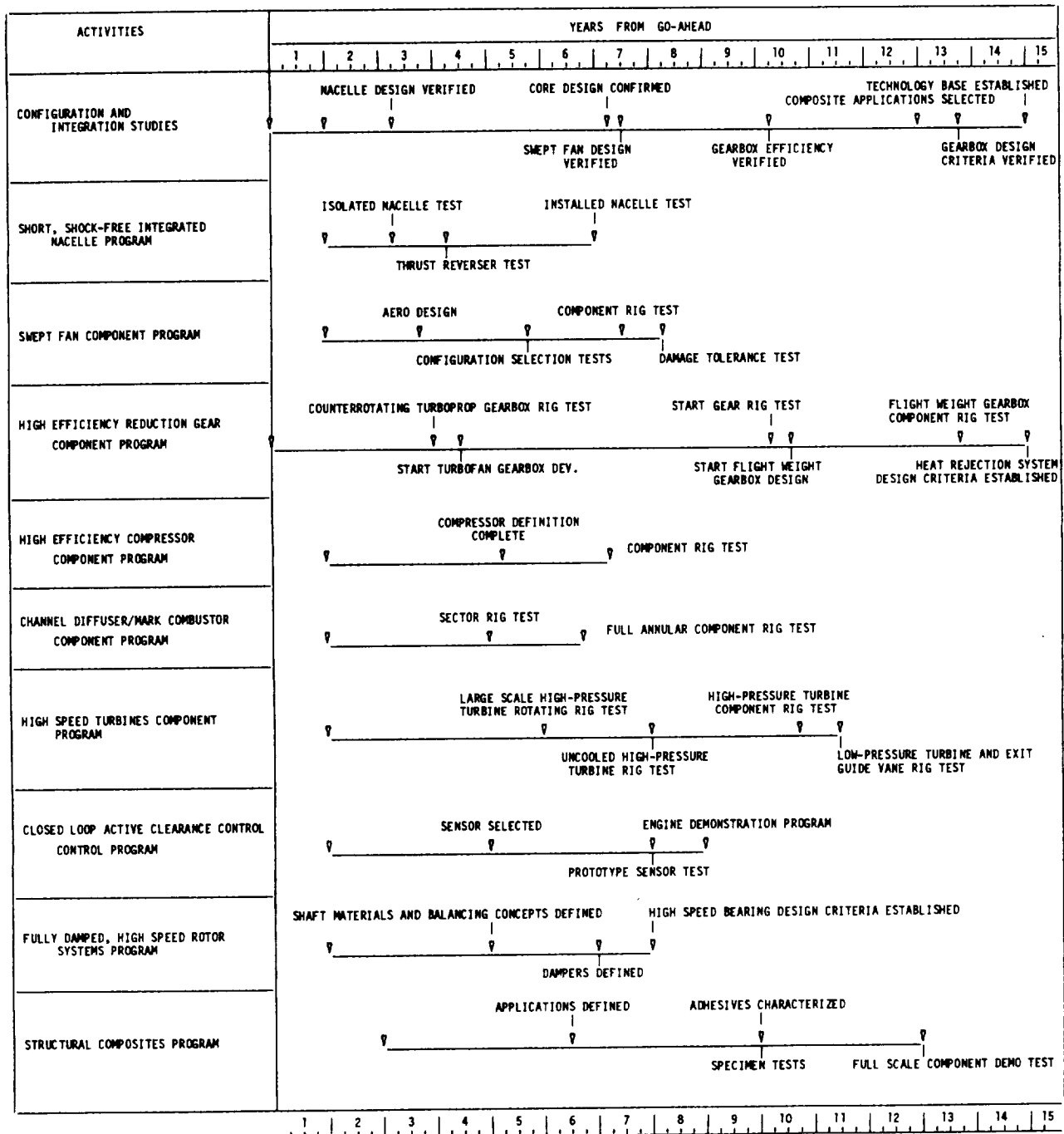


Figure 7 Technology Schedule -- This multi-year schedule shows the major technology programs, key milestones and estimated timing.

SECTION 6 -- CONCLUDING REMARKS

The benefits derived from technology advancements for future turbofan engines are significant and far from exhausted. The potential savings -- up to 24 percent in fuel burned and up to 14 percent in direct operating costs relative to a refined version of the Energy Efficient Engine -- translate into billions of dollars in annual savings for the airlines.

The development of a technology base that permits engines to operate at substantially higher overall pressure ratio and bypass ratios is mandatory to obtain these benefits. The technologies identified in this study are essential toward the achievement of this objective, and they require appreciable advances in the areas of aerodynamics, structures, cooling techniques, and materials.

The results of this study have pointed the direction for future research. The next major step is initiating the required programs that will turn the high technology into large payoffs.

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1. REPORT NO. NASA CR-174766		2. GOVERNMENT ACCESSION NO.		3. RECIPIENT'S CATALOG NO.	
4. TITLE AND SUBTITLE ENERGY EFFICIENT ENGINE PROGRAM TECHNOLOGY BENEFIT/COST STUDY - VOLUME I - EXECUTIVE SUMMARY				5. REPORT DATE October 1983	
				6. PERFORMING ORG. CODE	
7. AUTHOR(S) D. E. Gray and W. B. Gardner				8. PERFORMING ORG. REPT. NO. PWA-5594-258	
9. PERFORMING ORG. NAME AND ADDRESS UNITED TECHNOLOGIES CORPORATION Pratt & Whitney Engineering Division East Hartford, CT 06108				10. WORK UNIT NO.	
				11. CONTRACT OR GRANT NO. NAS3-20646	
12. SPONSORING AGENCY NAME AND ADDRESS NATIONAL AERONAUTICS AND SPACE ADMINISTRATION Lewis Research Center 21000 Brookpark Road, Cleveland, Ohio 44135				13. TYPE REPT./PERIOD COVERED Contractor Report	
				14. SPONSORING AGENCY CODE	
15. SUPPLEMENTARY NOTES NASA Project Manager, Mr. Frank Berkopec NASA - Lewis Research Center, 21000 Brookpark Rd., Cleveland, OH 44135					
16. ABSTRACT <p>Under the NASA sponsored Energy Efficient Engine program, Pratt & Whitney completed the Benefit/Cost Study to identify turbofan engine technologies required for the years 2000 to 2010, to assess the benefits of those technologies, and to formulate programs for developing the technologies required for that time period. The results of this study verified that there are still many potential benefits to be realized from the advancement of gas turbine engine technology.</p> <p>The initial effort in the program was to screen and rank preliminary technology concepts that might be amenable to future development. Cycle studies, flowpath definition studies, and mechanical configuration studies were then used to identify and establish the feasibility of the technologies that would be required in the 2000 to 2010 time frame. These efforts showed that a turbofan engine with advancements in aerodynamics, mechanical arrangements, and materials offered significant performance improvements over 1988 technology.</p> <p>The benefits of the technologies were assessed using fuel burn and direct operating cost plus interest (DOC+I). These concepts could yield thrust specific fuel consumption benefits of almost 16 percent, fuel burn benefits of up to 24 percent and DOC+I benefits of up to 14 percent in a long-range airplane relative to Energy Efficient Engine technology levels. Technology development programs have been formulated and recommended to realize those benefits.</p>					
17. KEY WORDS (SUGGESTED BY AUTHOR(S)) High Bypass Ratio Geared Turbofans Swept Fan Blades Energy Efficient Engine Future Turbofan Technology			18. DISTRIBUTION STATEMENT		
19. SECURITY CLASS THIS (REPT) UNCLASSIFIED		20. SECURITY CLASS THIS (PAGE) UNCLASSIFIED		21. NO. PGS	
				22. PRICE *	

FOREWORD

The Energy Efficient Engine Component Development and Integration program is being conducted under parallel National Aeronautics and Space Administration contracts with Pratt & Whitney and General Electric Company. The overall project is under the direction of Mr. Carl C. Ciepluch. The Pratt & Whitney effort is under contract NAS3-20646, and Mr. Frank Berkopec is the NASA project engineer responsible for the portion of the project described in this report. Mr. William B. Gardner is manager of the Energy Efficient Engine program at Pratt & Whitney. This report was prepared by Mr. D. E. Gray and Mr. W. B. Gardner of Pratt & Whitney.